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ABSTRACT

Recent tests performed at the NASA Glenn Research Center and elsewhere have shown promise in the design and construction of high voltage (300-1000 V) solar arrays for space applications. Preliminary results and implications for solar array design will be discussed, with application to direct-drive electric propulsion and space solar power.

INTRODUCTION

High voltage systems are used in space in order to save launch weight. First of all, for the same power level, higher voltages enable use of thinner wires (lighter cabling). This is because $P = IV$, and $V = IR$, so $P = I^2R$. If I is decreased by use of higher V, then the wire resistance can be increased, that is, thinner wires may be used, with no increase in power loss due to cabling. In the case of ISS, the decision to use a 160 V primary power system was based on the decreased cable mass possible. Of course, if one uses the same cable mass, higher voltages will enable higher efficiencies, as less power will be lost to resistance in the cables. For very large power systems, the decrease in cable mass can be substantial.

Secondly, some spacecraft functions require high voltages. For example, electric propulsion uses voltages from about 300 V (Hall effect thrusters) to about 1000 V (ion thrusters). For low voltage power systems, conversion of substantial power to high voltages is required for these spacecraft functions to operate. The weight of the power conversion systems (PMAD) can be a substantial fraction of the total power system weight in these cases. It is more efficient, and can save weight, if the high voltage functions can be directly powered from a high voltage solar array, for instance. If the high voltage function is electric propulsion, we call such a system a direct-drive electric propulsion system. Systems have been proposed that switch between parallel and series combinations of different strings of solar cells in order to facilitate occasional high voltage requirements, but to enable housekeeping functions at a lower voltage.

Solar arrays have proven to be the major source of reliable long-term electric power for both manned and unmanned orbital spacecraft. In the early days of spaceflight, a few satellites used energy sources other than solar arrays and batteries, such as fuel cells or thermo-electric prime power sources. By 1970, because of extended mission times as well as increased power requirements, the majority of spacecraft primary power systems used solar arrays and rechargeable batteries to supply the required 28 V. The choice of 28 volts for the main bus voltage was made to take advantage of long-existing standards and practices within the aircraft industry.

Plasma interactions at 28 V have not been generally considered a degradation factor of consequence. The only noted exceptions to their benign nature have occurred under extreme environmental conditions, especially during geomagnetic substorms for spacecraft operating at high inclinations. For low inclination spacecraft, those that completely avoid the auroral oval, 28-volt systems have not been observed to arc.

As the power requirements for spacecraft increased, however, high voltage solar arrays were baselined to minimize total mass and increase power production efficiency. With the advent of 100 V systems in the late 1980's, arcing began to be observed on a number of spacecraft solar arrays, damaging or disabling those spacecraft. For example, see Hoeber et al, 1998.

SOLAR ARRAY ARCING

As one might expect, the initiation of a solar array arc depends on the presence of a strong local electric field. Frequently the source is an exposed interconnect which, depending on its location in the string, can be at high potential.

Most problematic are arcs that initiate at triple points. A triple point is a point in space where insulator, conductor, and plasma all meet. For a solar cell operating in LEO this is usually the solar cell interconnect, but it can also be the edge of the solar cell (near the substrate or the coverslide). It has been shown that arcing on solar arrays at voltages less than about minus 1000 V is always intermediated by the presence of a plasma. Identical samples to those that arced at -100 V in a plasma have been shown to withstand -1000 V bias in a pure vacuum.

Arcs have been observed at relatively low potentials (as low as -75 V) when conductor surfaces are biased negative near insulator surfaces in the presence of a plasma. Arc rate is strongly dependent on plasma density and on coverslide temperature, which affects the surface conductivity. It may range from intermittent (on a scale of minutes and perhaps hours or longer), to several per second. Arc currents observed in ground tests are on the order of an ampere and may last several microseconds. These characteristics depend on the capacitance to space, increasing with increasing capacitance. These arcs are usually associated with solar cell array interconnects, but have also been observed on biased conductor surfaces covered with dielectric strips. They are likely to be of concern whenever conducting surfaces at negative potentials with respect to plasma abut insulating surfaces.

Vayner et al (2002) and Galofaro et al (2002) have shown that arcs at low voltages (~ -300 V) are always associated with contamination layers on conductors abutting insulators and exposed to the space plasma.

THE SUSTAINED ARC

When the arc circuit includes the solar arrays or other source of power, it may be possible for solar array arcs to become continuous (or sustained). Such continuous arcs, fed by the solar arrays, have an essentially inexhaustible source of energy, and can lead to catastrophic damage. This hypothesis for the loss of solar array strings on the SS/Loral satellites PAS-6 and Tempo II was confirmed by ground-tests done by Snyder et al (2000). Later testing on the EOS-AM1 arrays showed that continuous solar array arcs could occur in a LEO environment at a string voltage as low as

minus 100 to −120 V. The scenario for the catastrophic loss is given in Ferguson et al (1999), and is summarized here:

First of all, an ordinary solar array arc must get started. This will usually be at a triple-point as described above. In the case of the SS/Loral arrays, the differential voltage between solar array and plasma could have been as low as 100 V, for the SS/Loral arrays were using thin coverslides similar to the APSA cells, which arced at voltages as low as -75 V on orbit (PASP Plus results, Soldi and Hastings, 1997).

When the initial arc (sometimes called the trigger arc) is generated, it discharges only the local capacitance, but the arc plasma expands out from the arc site and comes in contact with an exposed conductor at a very different voltage. In the case of the SS/Loral arrays, the most positive end of the array strings was less than a millimeter away from the negative end. Now the arc plasma makes direct contact with the other conductor and makes for an almost dead short to that spot. The arc current has changed from one that is discharging capacitance to a current between two ends of the solar array string.

If the current available to the arc site from the functioning arrays is greater than a certain threshold value and the voltage between strings is above a certain value, the arc will become continuous. In ground tests these arcs continued until the source of power was artificially turned off. In space, presumable the arc would continue until the exposed conductors were melted through and the circuit was thereby interrupted. This could take seconds or minutes. Ground tests have shown that an arc that persists for more than a few hundred microseconds will not shut off by itself.

An arc that lasts long enough will locally heat the substrate and release gases. In the case of a kapton substrate, the kapton chars, but the char is also a good conductor, and provides a path for the arc to continue. Snyder et al (2000) have shown that the heat generated in continuous arcs on kapton is sufficient to produce the kapton charring measured after the event.

Sustained Arc on the EOS-AM1 Solar Array Test Sample.

In any event, a continuous arc can destroy a whole string (if the arc is between traces on the same string) or adjacent strings (if the arc is between strings) or the entire array power (if the arc is between combined power traces). The possibility of losing the entire array power on the Deep Space-One mission caused the builders to remove a solar panel that had already been installed to modify it and its sister array to prevent continuous arcing. Its power traces were only a few millimeters apart, and were exposed both to the plasma and to each other before the modifications were made. Afterwards, insulating material prevented arc plasma from shorting out between the power traces.

NEW DATA ON VOLTAGE AND CURRENT THRESHOLDS FOR SUSTAINED SOLAR ARRAY ARCING

Of great interest to solar array designers are techniques to prevent continuous (sustained)

arcing from occurring on space solar arrays. They may be prevented by preventing the initial (the so-called "trigger") arc from occurring, or by preventing the secondary plasma arc to adjacent strings from occurring.

Previous work at NASA GRC has shown that for each solar array design there is a voltage threshold for the trigger arc (Ferguson, 1986), and voltage and current thresholds for the sustained arcs (Hoeber et al, 1998). Trigger arc thresholds vary from about -100 to about -250 volts, depending on solar array design parameters, such as the thickness of the solar cell coverglasses and the amount of coverglass overhang beyond the cell edges. Sustained arc voltage thresholds can be less than the trigger arc thresholds. For instance, if two adjacent solar array string have a difference in cell voltage of 60 volts, but either is operating at -250 volts, a trigger arc can occur which will evolve into a sustained arc between strings.

Among the techniques used to prevent sustained arc discharges are preventing the array voltage from getting above the trigger arc threshold, lowering the voltage between adjacent strings to a value below its threshold and lowering the current that can get to the trigger-arc site below its threshold. If any of these values is less than the associated threshold, a sustained arc can't get started. Until the present work, the lowest known sustained arc voltage threshold was about 55 V. The present work showed that sustained arcs can occur at voltages as low as 40 V and currents as low as 1 amp.

Several solar array samples were tested in a simulated plasma in a vacuum-plasma chamber in the Plasma Interactions Facility (PIF) at NASA GRC. The plasma was produced by a Penning type source, using

xenon gas. The array panels were 3x12 solar cells, and the cells were 4x6 silicon cells on a Kapton® substrate. Adjacent strings were separated by 0.8 mm. The strings were biased to − 400 to −450 volts, and the voltage difference between strings was increased until the arcs produced became sustained arcs. The lowest sustained arc thresholds were obtained for solar cells for which the coverglass thickness was 300 microns (6 mils) and the coverglasses did not overhang the cell edges. For thinner (150 micron) coverglasses with no overhang, the thresholds found were 60 V and 2 amps. Coverglasses of 150 micron thickness and 250 micron (10 mil) overhang had thresholds of 80 V and 1.6 amp.

These new sustained arcing thresholds will allow array designers to prevent sustained arcing that could damage or destroy their satellite arrays in the harsh space environment.

PREVENTING TRIGGER ARCS

Recent work by Vayner et al (2001, 2002) and Galofaro et al (2002) has shown that trigger arcs are initiated by contaminant layers on conductors adjacent to insulators in contact with the space plasma. If thoroughly baked out in a vacuum-plasma chamber, samples which would otherwise arc at less than -200 volts did not arc at voltages well in excess of -500 V. In addition, spectra of the trigger arcs showed evidence of water contamination in the hydroxyl and Balmer line spectra of the arcs. This would suggest that a thorough bakeout of space solar arrays would increase their arc thresholds. However, condensable outgassing products may make that goal unachievable on-orbit. For instance, in LEO, the cold temperatures on the night side

of the orbit may condense out water and other outgassing products on the arrays. As an example, arc rates on the LEO satellite PASP Plus arrays did not change much even after a full year. Even GEO satellites undergo eclipses, which may "reset" the arcing properties of the arrays.

A better technique to prevent arcing may be encapsulation of the arrays, such that the space plasma is excluded from contact with conductor-insulator junctions. This was the tactic employed on the Solar Tiles from Boeing Phantomworks. As discussed in Reed et al (2001), arrays covered with a single large coverglass to prevent plasma contact resisted arcing even at voltages as high as -1100 V in GRC testing.
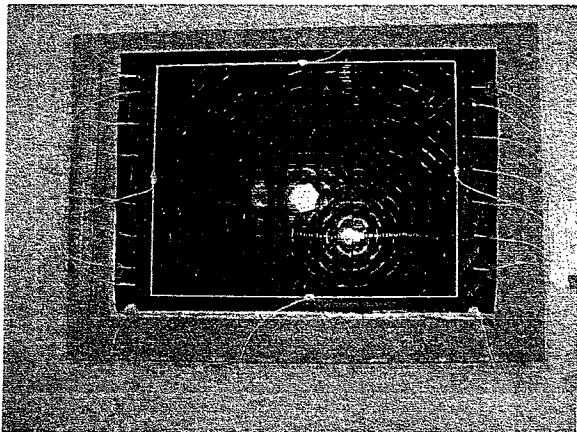

Boeing Phantomworks Solar Tile.

In this case, an initial tile's coverglass cracked due to entrained air when placed under a vacuum. Even the cracked tile resisted arcing at voltages in excess of -750 V. A new tile produced with greater care to preventing entrained air, while still sealing the tile from the plasma, succeeded in withstanding voltages up to -1100 V in a simulated space plasma without arcing.

In addition, a solar cell design encapsulating the edges of the solar cells has survived high

voltages in a plasma environment. The Entech Stretched Lens Array (SLA) design uses concentrating lenses to focus sunlight onto solar cell strings, and the edges of the solar cells are encapsulated to prevent plasma contact. In separate tests at Auburn University (O'Neill et al, 2001) and independently at NASA GRC (Ferguson et al, 2001), these cells did not arc at voltages as high as -1100 V even though damaged by simulated micrometeoroid impacts.
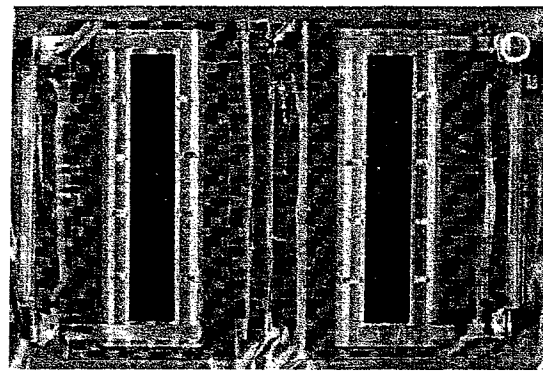
Entech SLA encapsulated cell sample.

THE HAZARDS OF ENCAPSULATION

One must be careful with the use of encapsulants, however, when the possibility exists of outgassing in the presence of high voltage components. For instance, on SAMPIE, one of the high voltage power supplies was destroyed by a Paschen discharge that occurred on a high voltage component where the encapsulant had delaminated and a neutral pressure was enclosed with the high voltage component (Ferguson and Hillard, 1997).

When encapsulating arrays or cells, several caveats must not be ignored. First, no air must be entrained anywhere. While this may seem obvious, at least one set of encapsulated test arrays sent to the Glenn Research Center had sufficient air entrained that the coating delaminated and swelled

under vacuum. In fact, so much air was entrained that the test articles under vacuum appeared to swell up like plastic balloons. In cases where only a very small amount of air is trapped, visible effects may not occur, yet the trapped air will present the danger of Paschen breakdown under high voltage.

Second, the encapsulant thickness must be sufficient to withstand dielectric breakdown at the highest array voltage. For thin-film arrays, this consideration can contribute significantly to the array mass. It is important that thin-film encapsulants be tested under voltage in a plasma environment, rather than relying solely on published dielectric strengths.

Third, the encapsulant must not be able to peel away from high voltage components, or Paschen breakdown can occur due to entrained outgassing products that may reach sufficiently high neutral pressures. For a wide range of pressure distance combinations, the Paschen minima are typically around a few hundred volts for common gases. Most outgassing products have not had their Paschen curves measured. In the case of solar arrays, a coverglass that covers many cells must also make allowances for escape of outgassing products from adhesives, as well. It must be treated for all intents and purposes as a vented encapsulant (see below).

Fourth, the encapsulant must be able to withstand other aspects of the space environment for its design lifetime. Atomic oxygen, micrometeoroids and debris, and UV and X-ray exposure are some of the threats to the encapsulant. Glass stands up well to all of these environments. Some plastics do not.

VENTED ENCAPSULANTS

To avoid plasma interactions, care must be taken that plasma does not enter the encapsulant and react with exposed conductors inside. The key requirement on such systems is that all openings must be smaller than the plasma Debye length, which depends on the plasma density and temperature. One can readily estimate the maximum opening consistent with such a requirement.

The plasma will be capable of maintaining electric fields over a distance of approximately one Debye length λ_D, which is given by

$$\lambda_D = (kT_e/4\pi ne^2)^{1/2} = 7.43 \times 10^2 (T_e/n)^{1/2}$$

where T_e is the electron temperature in eV, k is the Boltzmann constant, $\pi = 3.14159...$, e is the charge of the electron, and n is the electron density in cm^{-3}. Placing representative values from International Reference Ionosphere (IRI-86) simulations in the above equation, one finds a minimum Debye length from 0.12 cm at 1100 K to 0.17 cm at 2300 K.

Openings in an encapsulated array may have smaller dimensions than this minimum and still be able to prohibit plasma interactions with the experiment electronics. Larger openings may be used if covered with an electrically connected conductive wire mesh of spacing less than the minimum Debye length. To provide a reasonable margin of safety, a general guideline is that no opening should exceed 0.10 cm in its largest dimension. (Ferguson and Hillard, 2002).

In the case of the Entech solar cells which had been punctured by simulated micrometeoroids, the small size of the cracks and holes (much smaller than the

Debye length) prevented arcing even though they were gas permeable by nevertheless preventing plasma contact with the cell conductors.

CONCLUSIONS

Significant progress has recently been made in the design and construction of space solar arrays which resist trigger arcs to -1000 V and can resist sustained arcing. Ground tests of the array designs allow engineers to confidently prevent solar array arcing on orbit.

This is of greatest importance for space power systems that require high voltages, such as direct-drive electric propulsion (300-1000 V) and the Space Solar Power project (eventually 20 kV or more).

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